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14. ABSTRACT

The over-arching objective of this research was to improve the quantitative basis for prediction of the occurrence of Coronal Mass Ejections (CMEs) and their impact on space weather. The most directly useful discovery, from the point of view of Space Weather forecasting, is that a CME associated with an erupting X-ray sigmoid is more likely to have flux rope ("magnetic cloud") structure at 1 AU than an arbitrarily-selected CME. On impacting the magnetosphere, the sigmoid-associated flux ropes in our database all produced at least "moderate" (Dst > 50 nT) geomagnetic storms, and several produced major storms. Hence, not only are sigmoidal active regions more likely to erupt, as we showed in earlier work (Canfield Hudson & McKenzie 1999), they are more likely to cause significant storms when they do. Also discovered was a signature of impending eruption in H-alpha imaging spectra of active regions, which could be used to predict the occurrence of eruptions a few hours in advance, whereas the sigmoid signature is more useful on time scales of days. These discoveries have been documented in 11 publications and 26 presentations.

15. SUBJECT TERMS
solar coronal mass ejections; interplanetary magnetic clouds; geomagnetic storms

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FINAL REPORT

Grant: F49620-00-1-0128, "INITIATION OF CORONAL MASS EJECTIONS"

Report period: April 1, 2000 to September 30, 2002

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Report date: June 19, 2003

OBJECTIVES

- Improve the quantitative basis for prediction of the occurrence of Coronal Mass Ejections (CMEs) and their impact on space weather.
- Extend earlier work into the regime of quantitative prediction based on vector magnetograms, X-ray images, and other data
- Learn, through 3D MHD models, why active regions that are large, or show twisted fields, are the most likely sites of CMEs.
- Understand the form and characteristics of current singularities in 2D and 3D steady states, with emphasis on the effects of helicity.

ACCOMPLISHMENTS/NEW FINDINGS

Data Analysis

We developed a database of eruptive solar events that includes Mees Solar Observatory active region vector magnetograms, Yohkoh X-ray sigmoids, cusps and jets, interplanetary data from ACE, WIND and IMP, and geomagnetic indices. We used the database to study solar, interplanetary, and geophysical effects of erupting solar active regions. With this database we made new findings:

- A CME associated with an erupting coronal sigmoid is more likely to have flux rope (called "magnetic cloud") structure at 1 AU than an arbitrarily-selected CME (Leamon, Canfield, and Pevtsov, 2002). On impacting the magnetosphere, the flux ropes in our database all produced at least "moderate" (Dst > 50 nT) magnetic storms. This result has importance in Space Weather forecasting: it shows that not only are sigmoidal active regions more likely to erupt, as we showed in earlier work (Canfield Hudson & McKenzie 1999), they are more likely to cause significant storms when they do.

- The correlations between coronal and 1 AU properties of sigmoidal eruptions (most significantly, leading magnetic field direction) reverse at solar minimum, when sunspot polarity reverses, as opposed to solar maximum, when the global solar dipole reverses (Pevtsov & Canfield, 2001). In other words, eruptions associated with active regions do not follow the general rule, derived without regard to active region association, which says that the global solar dipole's orientation solely determines the leading polarity of the interplanetary magnetic cloud.

- The overall twist of active region magnetic fields is very small compared to that of interplanetary magnetic clouds that are associated with them (Leamon et al 2003, in preparation). Roughly speaking, the helical structure of magnetic clouds inferred from Bessell-function fits to the interplanetary data contains more than order of magnitude more turns than the sheared structure of active regions inferred from vector magnetogram. This discovery is important because the only models of CMEs that can explain this result are those that invoke magnetic reconnection to form the magnetic cloud from the pre-eruption corona.

- Yohkoh SXT image sequences of the shapes of 191 X-ray sigmoids and the histories of eruption (evidenced by cusp and arcade signatures) of their associated active regions reveal that the distribution of sigmoid shapes is quite narrow, confirming an earlier result by Rust and Kumar (1996), and the frequency of eruption does not depend significantly on shape (Leamon et al., 2003). We know of no explanation of this interesting clue about the origin of this phenomenon.

- Vector magnetograms give values of the large-scale total twist of active regions in which flare-related Yohkoh SXT signatures of eruption are observed (Leamon et al, 2003). We find no evidence of eruption for values of total twist remotely approaching the threshold for the kink instability. In other words, we find no evidence that the MHD kink instability plays a significant role in solar eruptions.

- We discovered a signature of impending eruption in H-alpha imaging spectra of active regions. This signature is present during a three-hour period before flares that are eruptive, but is absent prior those that are not (Des Jardins and Canfield, 2003). This is a statistically significant result, based on a study of 16 events. These properties could be used to predict the occurrence of eruptions a few hours in advance, whereas the sigmoid signature is more useful on time scales of days.

Finally, we wrote a review of sigmoids and eruptions (Canfield, Hudson, and Pevtsov 2000) for non-solar space weather researchers.

Theory and Modeling

We completed a 3-dimensional numerical MHD simulation of the emergence of twisted flux tubes into the corona. The simulation was initialized with a straight tube of twisted magnetic field located in the upper convection zone. Buoyancy drives an arched segment of a twisted flux tube upward through the photospheric layer and into the corona. Matter drains from the coronal field, which thereafter undergoes a rapid expansion and attains sigmoidal topology (Maraga and Longcope 2001). We discovered that magnetic field lines that emerge with a large aspect ratio (the ratio of height to footpoint separation) simply continue to expand into the outer atmosphere, while field lines emerging with a small aspect ratio do not (Magara 2001). This is a previously unknown aspect of the evolution of active regions.

We analyzed the injection of magnetic energy and magnetic helicity into the atmosphere during the simulated flux emergence (Magara & Longcope 2003). We found that the emergence contributions are the dominant ones at the early phase of flux emergence and that later that role is played by the shearing

contributions. The emergence starts with a simple dipole structure formed in the photosphere, which is subsequently deformed and fragmented, leading to quadrupolar structure.

We derived a new mathematical scheme for mapping the connectivity of a potential magnetic field arising from an arbitrary distribution of discrete sources (Longcope & Klapper 2002). The field lines interconnecting the sources are classified into domains, defining the field's connectivity. The scheme enables one to quantify how much energy is stored in active regions, and where it is stored in topological terms.

PUBLICATIONS

Canfield, R. C., Hudson, H. S., and Pevtsov, A. A., "Sigmoids as Precursors of Solar Eruptions", IEEE Transactions on Plasma Science, IEEE Transactions on Plasma Science, 28, 1786, 2000.

Des Jardins, A.C. & Canfield, R.C., "Preflare Phenomena in Eruptive Flares", Astrophys. J., in press (2003).

Klapper, I., "Long Time Behavior of Magnetic Field in Two Dimensions", Proceedings of the Royal Society of London, (A), 459, 1053, 2003.

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Longcope, D. W., and Klapper, I. K., "A General Theory Of Connectivity And Current Sheets In Coronal Magnetic Fields Anchored To Discrete Sources," Astrophys. J. 579, 468, 2002.

Magara, T. and Longcope, D. W. "Sigmoid Structure of an Emerging Flux Tube", Astrophys. J. 559L, 55, 2001.

Magara, T. "Dynamics of Emerging Flux Tubes in the Sun, ApJ, 549, 608, 2001.

Magara, T. & Longcope, D. W., "Injection of Magnetic Energy and Magnetic Helicity into the Solar Atmosphere by an Emerging Flux Tube", Astrophys. J., 586, 630, (2002).

Pevtsov, A. A. and Canfield, R. C. "Solar Magnetic Fields and Geomagnetic Events", JGR, 106, 25191, 2001.

Magara, T. & Longcope, D. W., "Three Dimensional MHD Simulation of an Emerging Flux Tube in the Sun" in "Multi-Wavelength Observations of Coronal Structure and Dynamics", COSPAR Colloquia Series Volume 13, P.C.H. Martens and D. Cauffman (eds.), 291, 2002.

PRESENTATIONS

Canfield, R. C., "The Sun Earth Connection in the Space Age", Distinguished Leaders in Science lecture series, National Academy of Science, Washington, DC, 11 May, 2000.

Canfield, R. C., "S Marks the Spot", AF Science Advisory Board Meeting, Hanscom Field MA, November 2000.

Colman, A. M., & Canfield, R. C., "Preflare Phenomena in Eruptive Flares", AGU/SPD Meeting, Boston MA, May 2001.

Colman, A. M., & Canfield, R. C., "Preflare Phenomena in Eruptive Flares", SHINE meeting, Snowmass CO, June 2001.

Klapper, I., "Restrictions on Finite Time Current Sheet Formation in Ideal 2D MHD", Isaac Newton Institute of Mathematical Sciences, Cambridge, UK, Nov. 2000.

Klapper, I., "Long Time Evolution of Magnetic Field in 2 Dimensions", Seminar, program on solar magnetism and related astrophysics, Institute of Theoretical Physics, University of California at Santa Barbara, March 2002.

Klapper, I., "Towards a General Theory of Fast Dynamos", Seminar, Courant Institute of Mathematics, New York University, May 2002.

Leamon, R. J., Canfield, R.C., and Pevtsov, A.A., "Properties Of Magnetic Clouds Resulting From Eruption Of Coronal Sigmoids", AGU/SPD Meeting, Boston MA, May 2001.

Leamon, R. J., Canfield, R.C., and Pevtsov, A.A., "Properties Of Magnetic Clouds Resulting From Eruption Of Coronal Sigmoids", SHINE meeting, Snowmass CO, June 2001.

Leamon, R.J., Canfield, R.C., Blehm, Z. and Pevtsov, A.A., "What Is The Role Of The Kink Instability In Eruption Of X-Ray Sigmoids?" AGU Spring meeting, Washington DC, May 2002.

Leamon, R.J., Canfield, R.C., Blehm, Z. and Pevtsov, A.A., "What Is The Role Of The Kink Instability In Eruption Of X-Ray Sigmoids?" NSF/SHINE workshop, Banff, AB, August 2002.

Longcope, D. W., "Reconnection and Helicity in the Coronal Magnetic Field", Seminar at The University of St. Andrews, UK, July 2000.

Longcope, D.W. "Topological Defects in Coronal Magnetic Fields: A Theory for Equilibrium Current Sheets in Complex Geometries", ITP Seminar, University of California, Santa Barbara, March 2002.

Longcope, D.W., "Transition Of Emerging Flux From Sub-Photospheric To Chromospheric Conditions, Chromosphere-Corona Coupling", Sac Peak Workshop, Sacramento Peak, NM, March 2002.

Longcope, D.W., "Connectivity And Current Sheets In General Coronal Magnetic Fields Through Constrained Variational Methods", AAS/SPD Meeting, Albuquerque, NM June 2002.

Lundberg, B.J., Leamon, R.J., and Canfield, R.C., "Helicity Of A Magnetic Cloud And Its Progenitor Active Region", NSF/SHINE workshop, Banff, Alberta, August 2002.

Magara, T., "Simulations of Emerging Flux Tubes", Solar Physics Seminar, Montana State University, Bozeman, April 2000.

Magara, T., "Expansion Process of Emerging Flux Tube", AAS Solar Physics Division meeting, Lake Tahoe, NV, June 2000.

Magara, T. and Longcope, D. W. "3-dimensional MHD Simulation of Emerging Flux Tubes" Astronomical Society of Japan spring meeting, Chiba, Japan, March 2001.

Magara, T. and Longcope D. W. "3-dimensional MHD Simulation of Emerging Flux Tubes" SHINE meeting, Snowmass CO, June 2001

Magara, T. and Longcope, D. W. "3-dimensional MHD Simulation of Emerging Flux Tubes" AGU/SPD meeting, Boston MA, May 2001.

Magara, T. and Longcope, D. W., "Sigmoid Structure of an Emerging Flux Tube", Yohkoh 10th Anniversary Meeting, Hawaii, January 2002.

Magara, T. and Longcope, D. W. "3-dimensional Evolution of an Emerging Flux Tube in the Sun", Astronomical Society of Japan spring meeting, Mito, Japan, March 2002.

Magara, T. and Longcope, D. W. "3-dimensional Evolution of an Emerging Flux Tube in the Sun", AAS/SPD Meeting, Albuquerque, NM June 2002.

Magara, T. and Longcope D. W. "3-Dimensional Evolution of a Magnetic Flux Tube Emerging into the Solar Atmosphere", SHINE meeting, Banff, Alberta, Canada, August 2002.

Zarro D.M., Canfield, R.C., Demoulin, P., Nitta, N., Myers, D.C., Gregory, S.E., Qiu, J., Alexander, D., Hudson, H.S. Thompson, B.J., LaBonte, B.J., "Max Millennium/Whole Sun Month Observations of a Sigmoid Region (AR 8668)", AAS Solar Physics Divsion meeting, Lake Tahoe, NV, June 2000.

HONORS/AWARDS

Dana Longcope was one of 59 scientists nationwide to receive the 2001 Presidential Early Career Award for Scientists and Engineers. The PECASE awards are "the highest honor bestowed by the U.S. government on outstanding scientists and engineers beginning their independent careers," according to a White House press release. See http://solar.physics.montana.edu/sol_phys/topaward.html for details.

Angela Colman won an AGU/SPA Outstanding Student Paper Award for Colman, A. M., & Canfield, R. C., "Pre-flare Phenomena in Eruptive Flares", AGU/ AAS-SPD Meeting, Boston MA, May 2001.

PROFESSIONAL ACTIVITIES

Richard Canfield:	Editorial Board, Solar Physics
Dana Longcope:	Sun Earth Connection Advisory Committee, NASA
	Solar-Heliospheric MOWG, NASA (Chair)
	Committee, Solar Physics Division